Exploring EFTs of Gauged Chiral Symmetries at the LHC and Beyond

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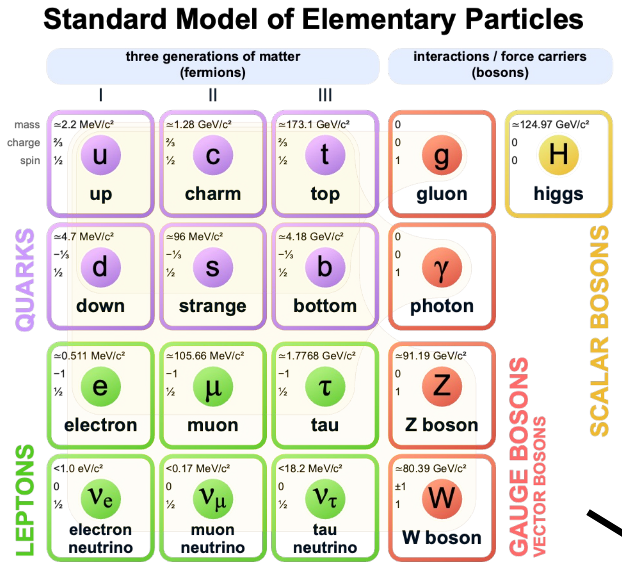
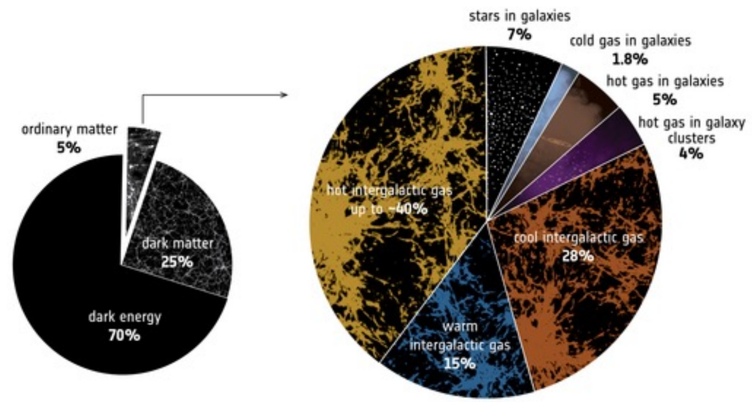
High Energy Theory Seminar, Brookhaven National Laboratory
January 22, 2026

With the Standard Model now complete, we are on a global hunt for **New Physics**

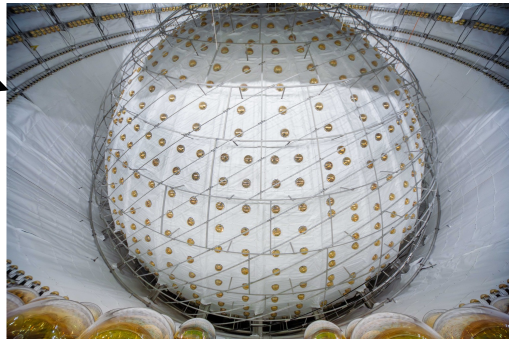


+ many more

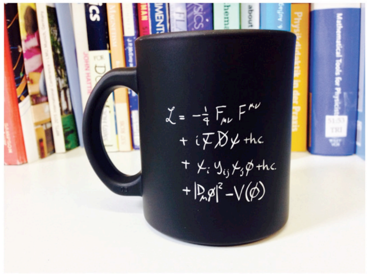
DM, DE



Origin of νs



Baryon asymmetry



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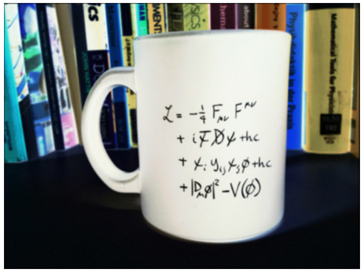


New particles, new interactions

In QFT, chiral symmetry permeates…

- As a structural aspect of 4D spacetime
  - Rotations and boosts of the Lorentz group can be reshuffled into an $SU(2)_L \times SU(2)_R$ algebra
    - Leads to irreducible LH or RH 2-comp. Weyl representations
  - Starting point for spinor-helicity formalism for amplitudes

$$[J_i, J_j] = i\epsilon_{ijk} J_k \ , \quad [J_i, K_j] = i\epsilon_{ijk} K_k \ , \quad [K_i, K_j] = -i\epsilon_{ijk} J_k$$

$$\Rightarrow$$

$$[J_i^+, J_j^+] = i\epsilon_{ijk} J_k^+ \ , \quad [J_i^-, J_j^-] = i\epsilon_{ijk} J_k^- \ , \quad [J_i^+, J_j^-] = 0 \ ,$$

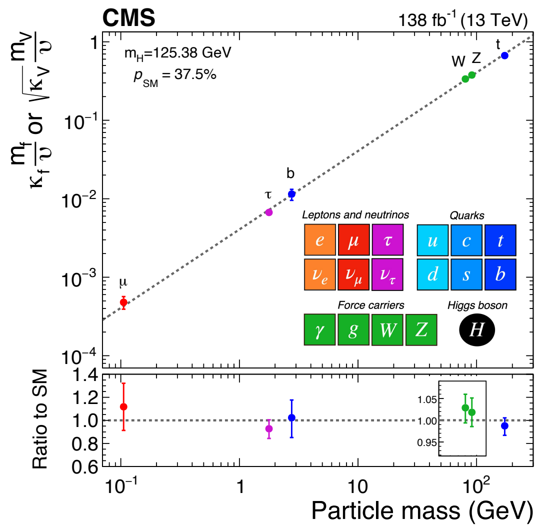
$$J_i^+ = \frac{1}{2}(J_i + iK_i) \text{ and } J_i^- = \frac{1}{2}(J_i - iK_i)$$

In QFT, chiral symmetry permeates…

- As a structural aspect of 4D spacetime
- As gauge and global group structure of the SM
  - Self-evident with the electroweak gauge group
    - No vector-like reps. for fermions and minimal Higgs content enforces no tree-level FCNCs, Higgs low-energy theorems, new physics flavor problem
    - Chiral couplings are an essential aspect of EW loop calculations

Predictive nature of **SM Higgs physics** is controlled by chiral symmetry

Non-decoupling top quark dof gives Higgs low-energy theorems



In QFT, chiral symmetry permeates...

- As a structural aspect of 4D spacetime
- As gauge and global group structure of the SM
  - Self-evident with the electroweak gauge group
  - Crucial for QCD chiral Lagrangian and hadron spectroscopy

Chiral effective Lagrangian from $N_F = 3$ QCD models phenomenology of mesons via quark condensate ansatz

$$\langle \bar{q} q \rangle \equiv v^3$$

$$\bar{u}_L u_R \approx |\langle \bar{u}_L u_R \rangle| \exp\big(i(\theta_{\pi^0} + \theta_{\eta'})\big) = \frac{v^3}{2} \exp\big(i(\theta_{\pi^0} + \theta_{\eta'})\big) \ ,$$

Meson spectroscopy leads to famous U(1) problem

$$\bar{d}_L d_R \approx |\langle \bar{d}_L d_R \rangle| \exp\big(i(-\theta_{\pi^0} + \theta_{\eta'})\big) = \frac{v^3}{2} \exp\big(i(-\theta_{\pi^0} + \theta_{\eta'})\big) \ ,$$

Phase counting leads to Strong CP problem

$$\bar{s}_L s_R \approx |\langle \bar{s}_L s_R \rangle| \exp\big(i\theta_{\eta'}\big) = \frac{v^3}{2} \exp\big(i\theta_{\eta'}\big) \sim \frac{v^3}{2} \ ,$$

Kivel, Laux, FY, JHEP **11** (2022) 088 [2207.08740]

In QFT, chiral symmetry permeates…

- As a structural aspect of 4D spacetime
- As gauge and global group structure of the SM
- As a possible feature of New Physics
  - Anomaly cancellation imposes a self-consistency requirement on NP dofs
  - MSSM and chiral superfields
  - PQ mechanism and axion solution as well as massless up quark solution to nEDM and strong CP
  - Fundamental Majorana nature of neutrinos?
  - Baryogenesis and new sources of CP violation
    - EW sphaleron reprocessing of B+L violation
  - + many open questions, *e.g.* chiral gauge groups at strong coupling

Goal: study gauged chiral EFT

- Effective Field Theory is perhaps our most powerful tool to characterize new physics and BSM extensions
  - Scale separation affords framework to capture wide classes of ultraviolet completions to the SM
- Will particularly focus on gauged chiral extensions of SM and their effective description
  - Such descriptions generally exhibit non-decoupling
  - NP chiral symmetry can be orthogonal to SM chiral symmetry
    - Exhibit interplay of misaligned Higgsed/unbroken phases

Global vs. gauged chiral symmetry

- Will focus on **gauged** chiral symmetries
  - Chiral anomalies (Adler-Bell-Jackiw) must cancel in UV
  - 't Hooft anomaly matching prescribes chiral transformations are inherited across phase boundaries
    - For example, pion decay to two photons via global $(U(1)_{EM})^2$ anomaly
  - One goal: construct an observable to "measure" gauge chiral anomaly

Michaels, FY, *JHEP **03** (2021) 120 [2010.00021]*

- *Aside: extending SM via a new **global** chiral symmetry is basis for axion physics*

Outline

- Introduction and motivation – chiral symmetry as a guiding principle for New Physics
- $U(1)_B$ model and field content
- Collider physics of new scalar ϕ
  - Z′-fusion and Higgsstrahlung production, decay patterns
  - Unmixed vs. mixed ϕ-h scenarios
- Z-Z′-γ vertex, measuring a chiral gauge anomaly
  - Conjecture: dim. reg., naïve γ^5, and momentum-shift invariance
- Conclusions

U(1)$_B$ model and field content

- SM has global U(1)$_B$ x U(1)$_L$ symmetry
  - Can gauge any combination of B and L without modifying Yukawas
  - Focus on gauged U(1)$_B$ $\mathcal{L}_q = \frac{g_B}{6} Z'_\mu \sum_q \bar{q}\gamma^\mu q$
  - Must introduce new EW fields and assign charges to cancel mixed anomalies = "anomalons"

$$\mathcal{A}(SU(2)^2 \times U(1)_B) = \frac{3}{2} \qquad \mathcal{A}(U(1)_Y^2 \times U(1)_B) = \frac{-3}{2}$$

  - Additionally, choose charges to satisfy the trace condition and suppress kinetic mixing

$$L_L(2, -\frac{1}{2}, -1),\ L_R(2, -\frac{1}{2}, 2), \quad E_L(1, -1, 2),\ E_R(1, -1, -1),$$
$$N_L(1, 0, 2),\ N_R(1, 0, -1)$$

$U(1)_B$ spontaneous symmetry breaking

- Introduce Φ (B-charge = +3) to spontaneously break $U(1)_B$

$$\mathcal{L} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + |D_\mu \Phi|^2 - \mu_\Phi^2 |\Phi|^2 - \lambda_\Phi |\Phi|^4$$

$$M_{Z'} = 3 \tfrac{g_B}{2} v'$$

  - Anomalons have two vevs for mass mechanism

$$\mathcal{L}_{\text{Yuk}} = -y_L \bar{L}_L \Phi^* L_R - y_E \bar{E}_L \Phi E_R - y_N \bar{N}_L \Phi N_R$$
$$- y_1 \bar{L}_L H E_R - y_2 \bar{L}_R H E_L - y_3 \bar{L}_L \tilde{H} N_R - y_4 \bar{L}_R \tilde{H} N_L + \text{h.c.} \ ,$$

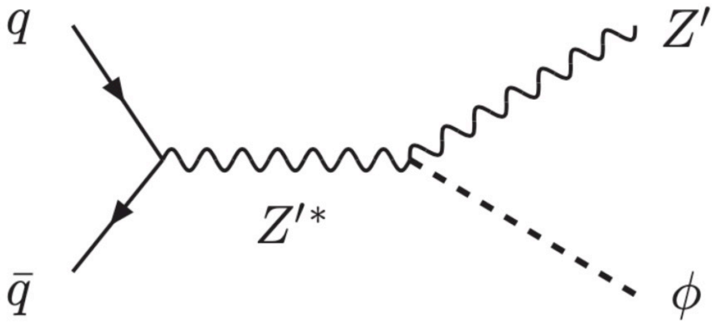
    - Set all Yukawas nonzero to avoid accidental Z_2 parity (stable charged particles)
      - Small y_1 and y_2 couplings give negligible effect on Br(h→γγ)
    - Will effective description with anomalons heavy, and dynamical Z′ and ϕ dofs
      - Contrast ϕ vs. other gauge-singlet scalars S (used, *e.g.*, for SFOPTs)

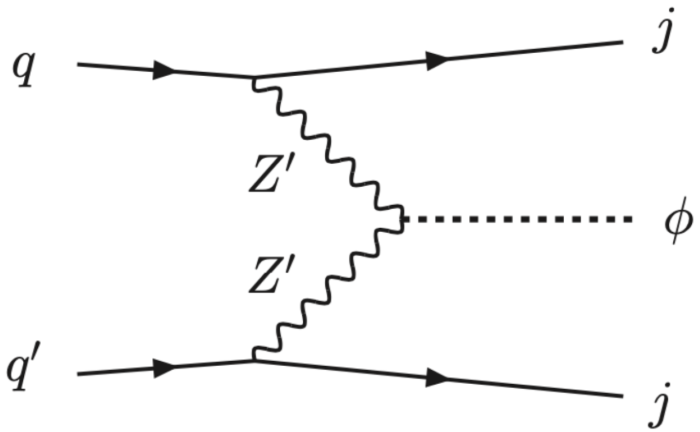
QUARK-UNIVERSAL U(1) BREAKING SCALAR AT THE LHC

Lorin Armbruster, Bogdan A. Dobrescu, FY [2506.06806]
Accepted by Physical Review D

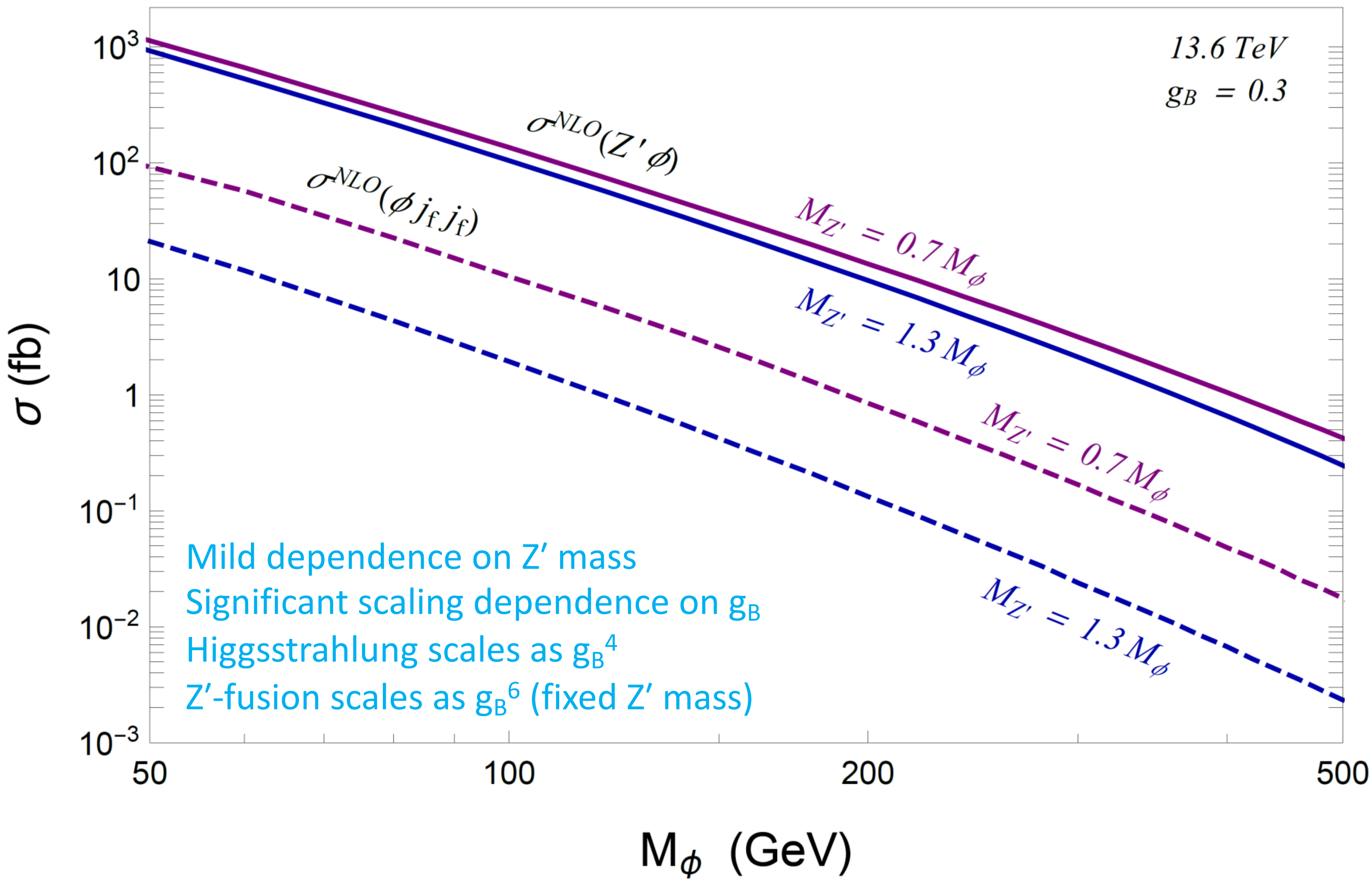
Cross sections for ϕ

- First consider case with no ϕ-h mixing
- Leading production modes are "familiar" Higgsstrahlung and Z′-fusion



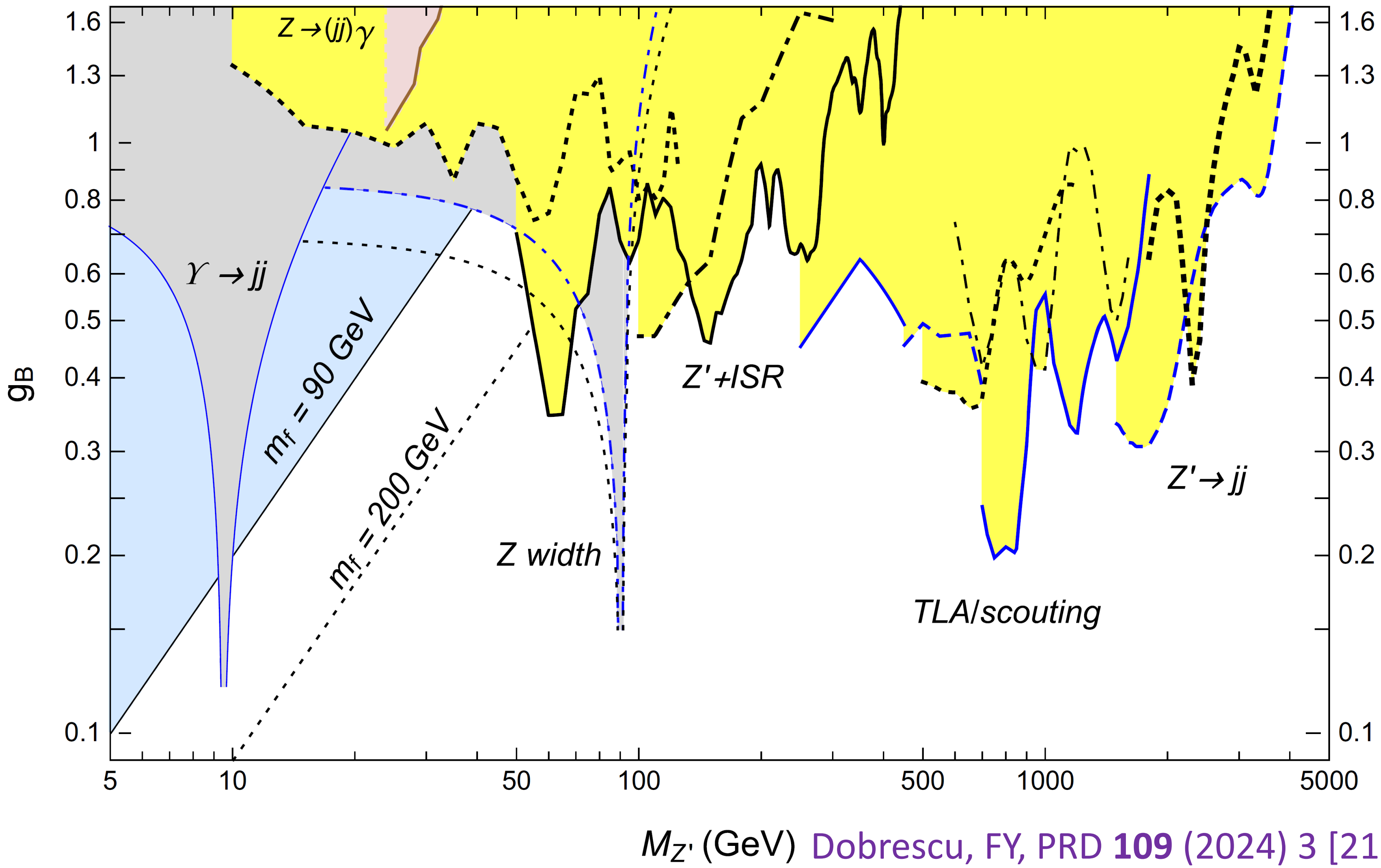


Cross sections for ϕ



Mild dependence on Z′ mass
Significant scaling dependence on g_B
Higgsstrahlung scales as g_B^4
Z′-fusion scales as g_B^6 (fixed Z′ mass)

Current status of dijet resonance searches

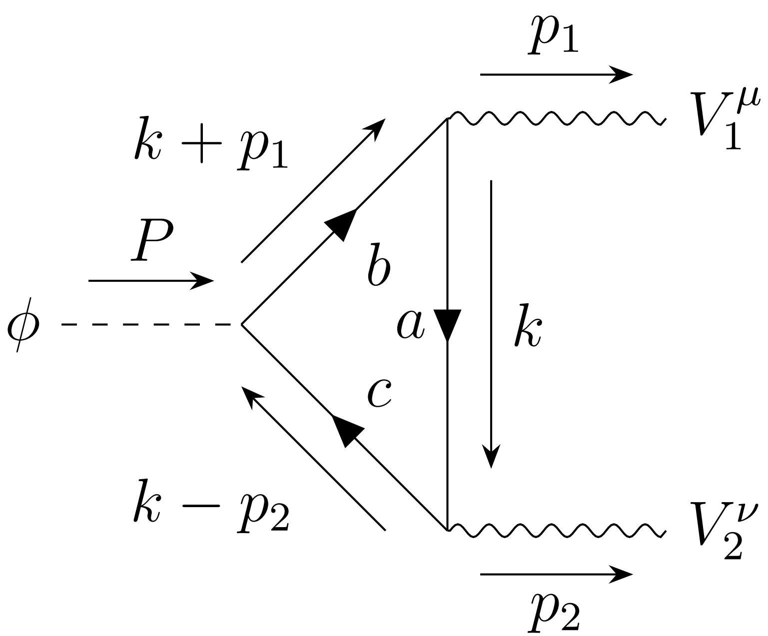


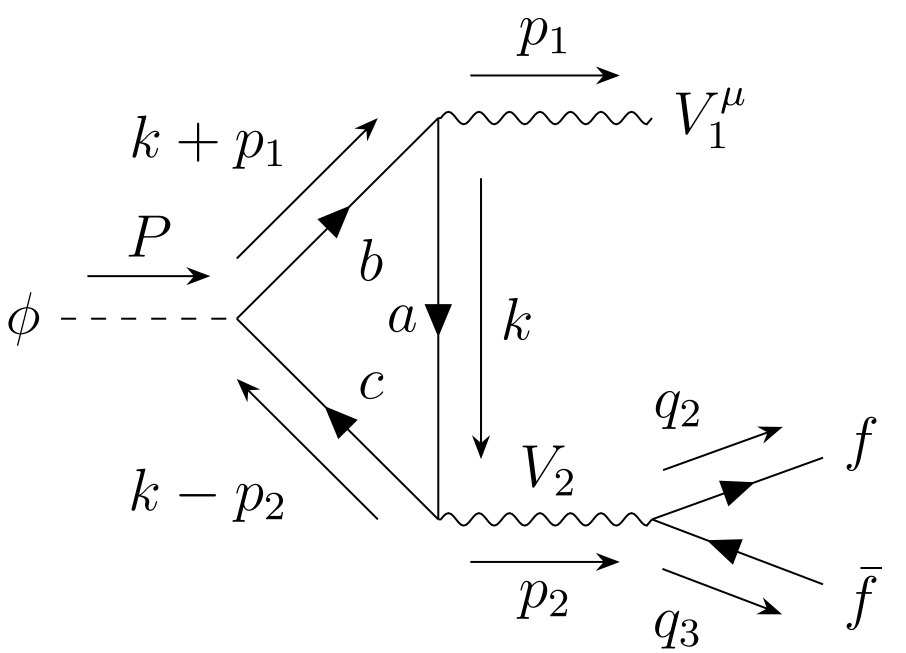
Dobrescu, FY, PRD **109** (2024) 3 [2112.05392]

Decays of ϕ

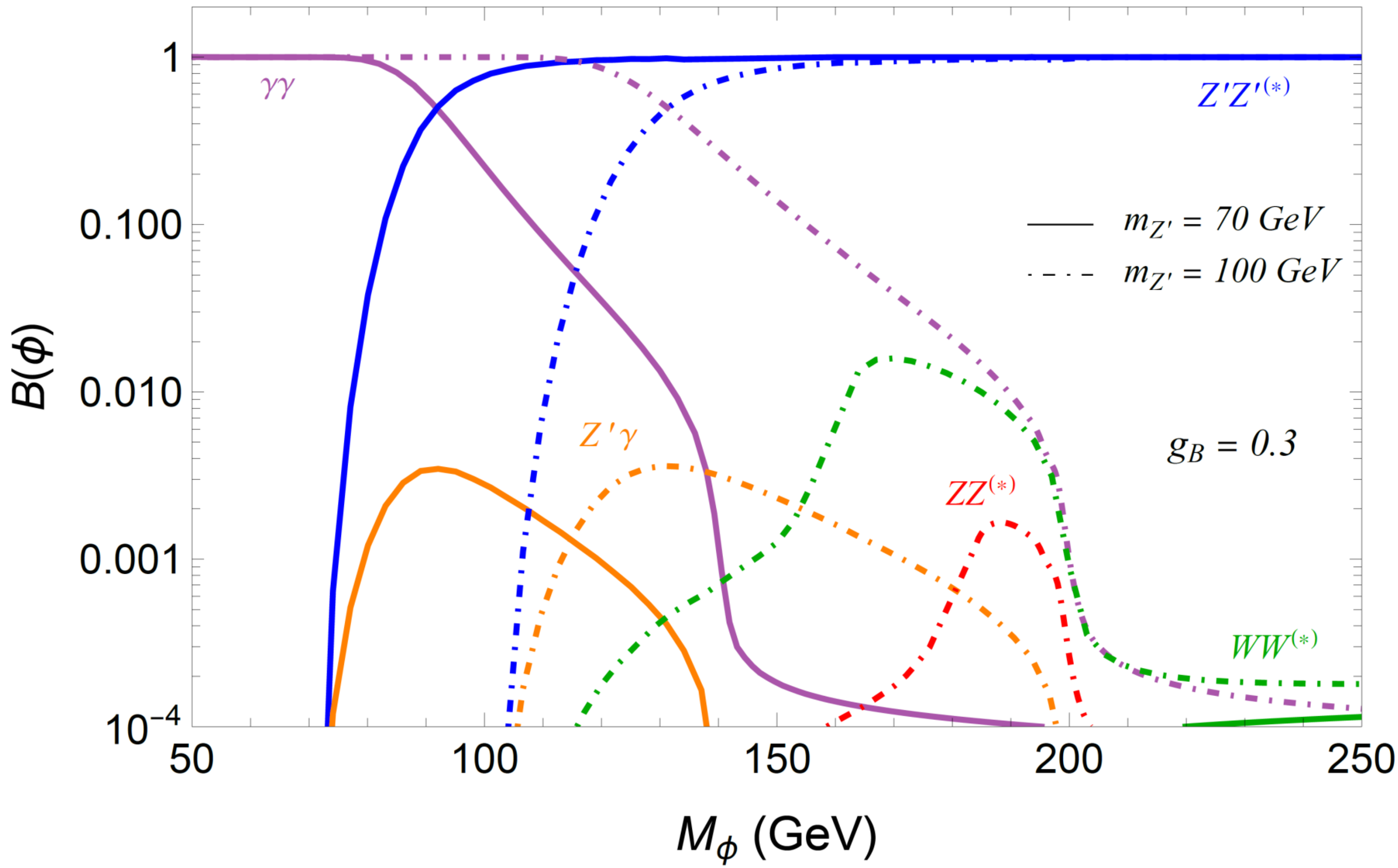
- For finite but heavy anomalon limit (M_1 = 200 GeV, M_2 = 250 GeV), only tree-level decay is $\phi \to Z'Z'$
  - When $M_\phi < 2 M_{Z'}$, one-loop decays of ϕ to $V_1 V_2$ or $V_1 f\bar{f}$ are most relevant

$V_1V_2 = \gamma\gamma, Z'\gamma, WW, ZZ, Z'Z, Z\gamma$



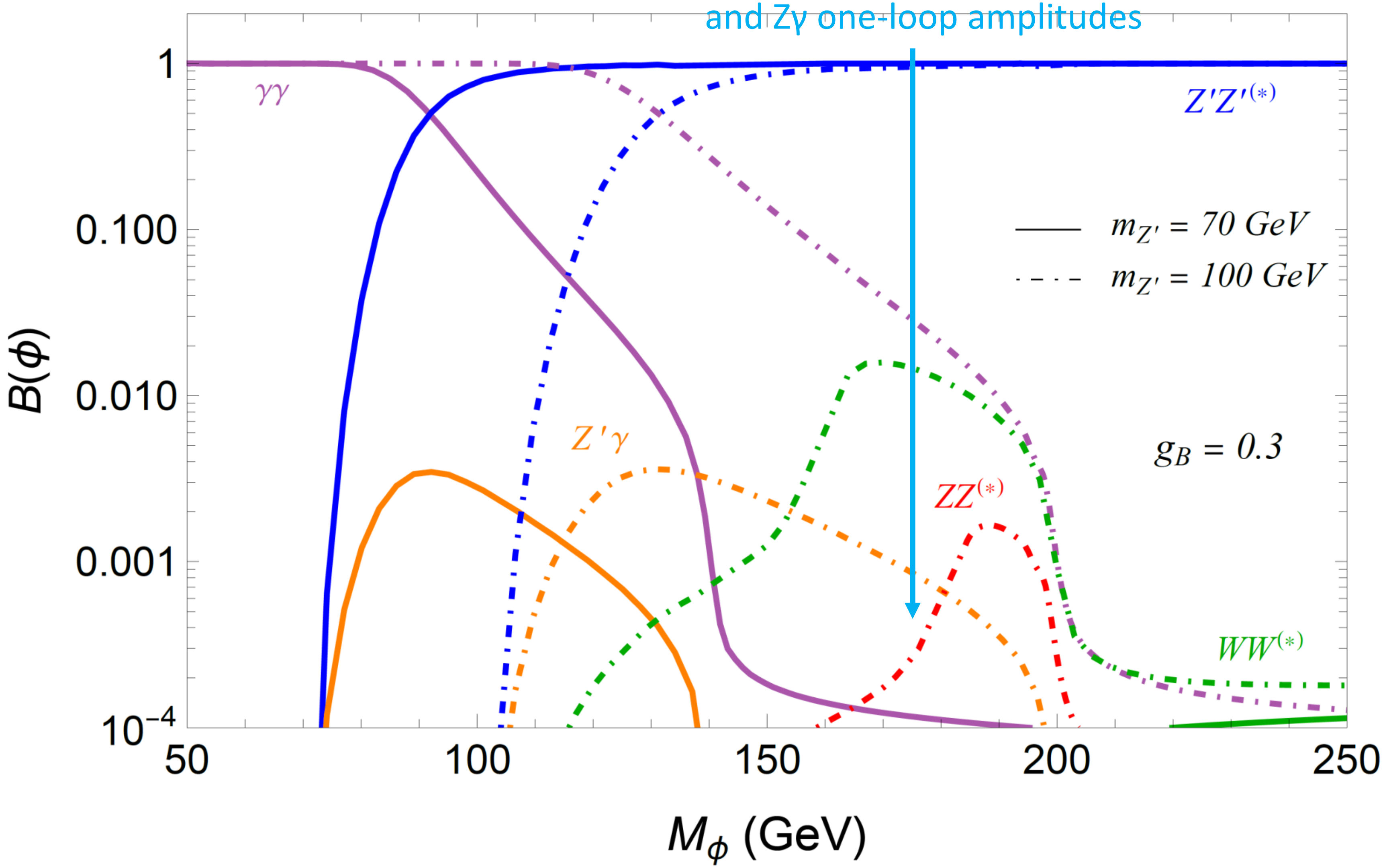


Decays of ϕ



Decays of ϕ

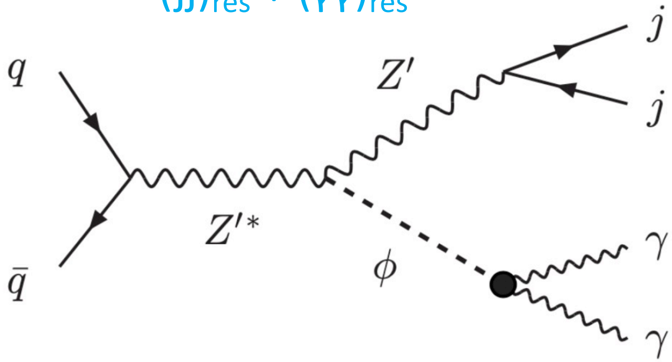
One curious feature: Z+ffbar decay includes interference with ZZ′, ZZ, and Zγ one-loop amplitudes



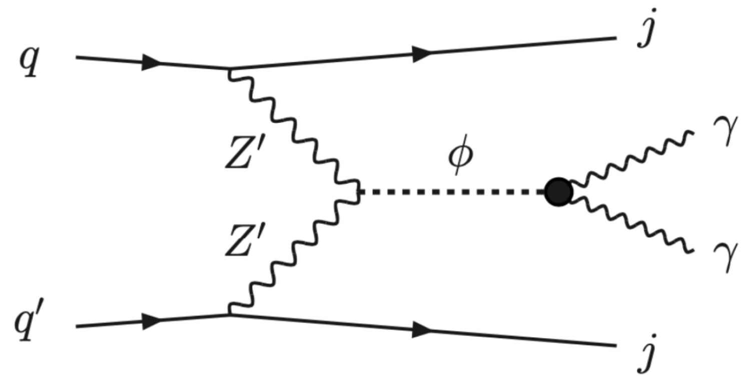
Suite of collider signatures

- Stitch together production and decay

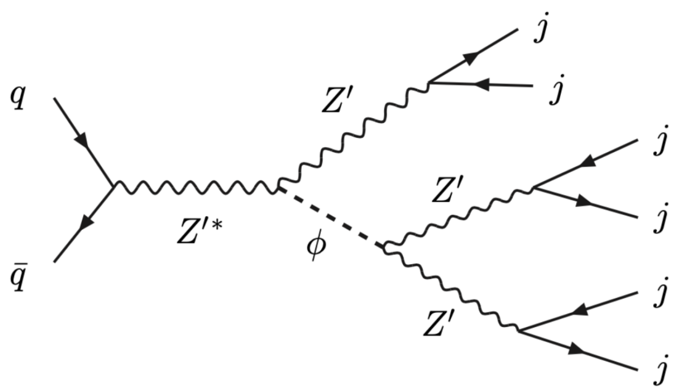
$(jj)_{res} + (\gamma\gamma)_{res}$



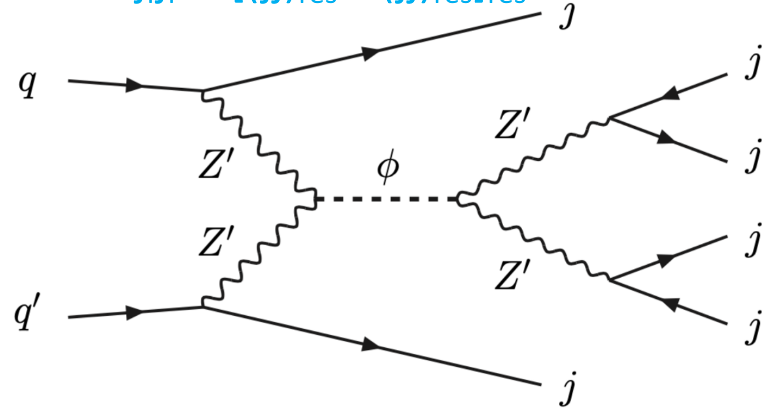
$j_f j_f\ (\gamma\gamma)_{res}$



$(jj)_{res} + [(jj)_{res} + (jj)_{res}]_{res}$



$j_f j_f + [(jj)_{res} + (jj)_{res}]_{res}$



Cross sections with Higgs mixing

- Now, incorporate scalar mixing angle α_h

$$V(\Phi, H) = \lambda_\Phi \left(|\Phi|^2 - \frac{v_0'^2}{2} \right)^2 + \lambda_H \left(H^\dagger H - \frac{v_0^2}{2} \right)^2 + 2\lambda_p |\Phi|^2 H^\dagger H$$

$$v'^2 = \lambda_H \frac{\lambda_\Phi \, v_0'^2 - \lambda_p \, v_0^2}{\lambda_H \, \lambda_\Phi - \lambda_p^2}$$

$$v_h^2 = \lambda_\Phi \frac{\lambda_H \, v_0^2 - \lambda_p \, v_0'^2}{\lambda_H \, \lambda_\Phi - \lambda_p^2}$$

$$\sin \alpha_h \approx \frac{\lambda_p \, v_h v'}{\lambda_\Phi \, v'^2 - \lambda_H \, v_h^2}$$

- Current mixing angle constraints from overall signal strength – gauge singlet scalar mixing

$$\mu_{\rm ATLAS} = 1.05 \pm 0.06$$
$$\mu_{\rm CMS} = 1.002 \pm 0.057$$
$$\rightarrow \mu_{\rm LHC} = 1.026 \pm 0.041 \longrightarrow \sin \alpha_h \le 0.24$$

CMS, Nature **607** (2022) [2207.00043]
ATLAS, Nature **607** (2022) [2207.00092]

Cross sections with Higgs mixing

- Now, incorporate scalar mixing angle

$$V(\Phi, H) = \lambda_\Phi \left(|\Phi|^2 - \frac{v_0'^2}{2} \right)^2 + \lambda_H \left(H^\dagger H - \frac{v_0^2}{2} \right)^2 + 2\lambda_p |\Phi|^2 H^\dagger H$$

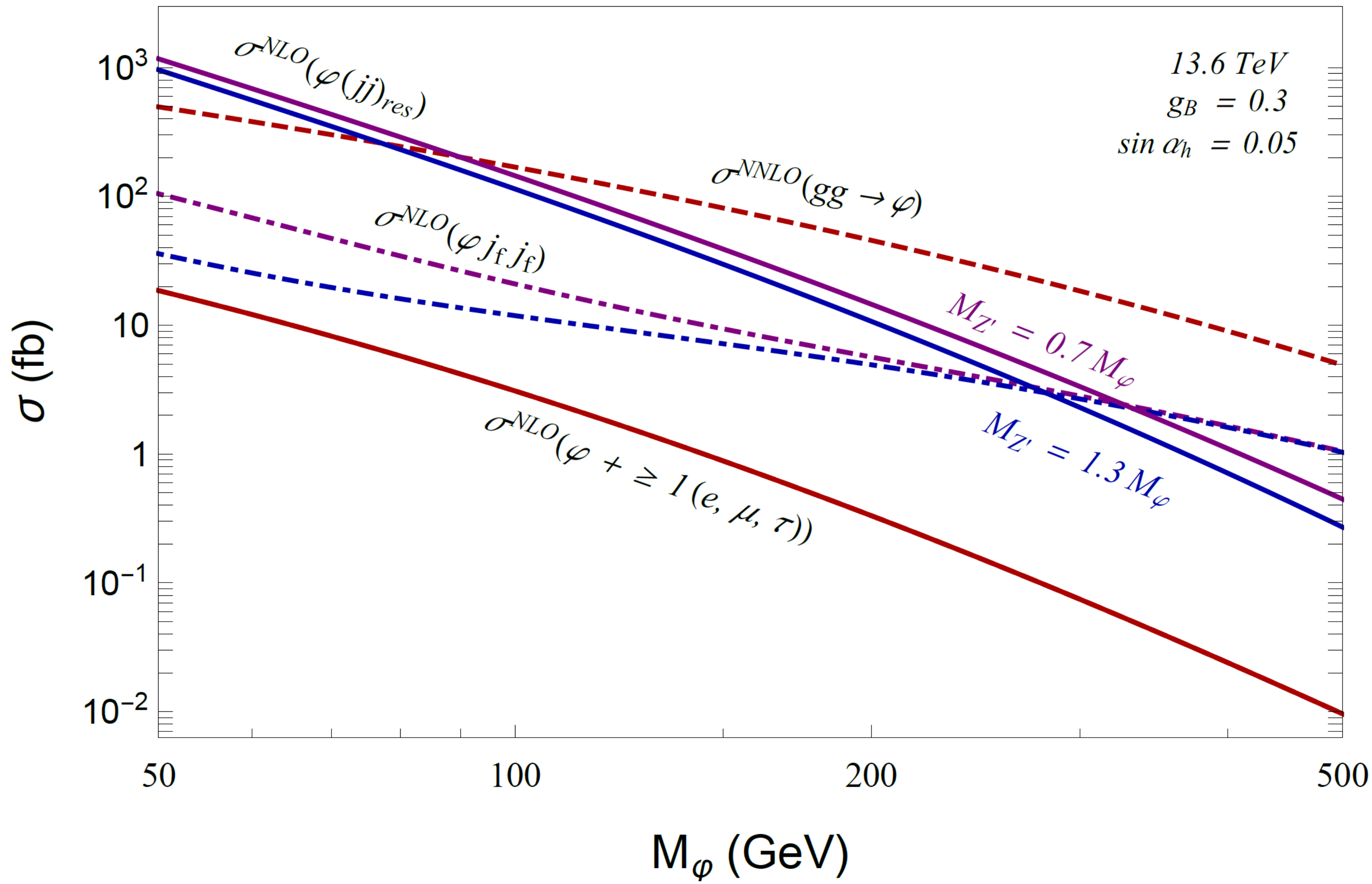
$$v'^2 = \lambda_H \frac{\lambda_\Phi\, v_0'^2 - \lambda_p\, v_0^2}{\lambda_H\, \lambda_\Phi - \lambda_p^2}$$

$$v_h^2 = \lambda_\Phi \frac{\lambda_H\, v_0^2 - \lambda_p\, v_0'^2}{\lambda_H\, \lambda_\Phi - \lambda_p^2}$$

$$\sin \alpha_h \approx \frac{\lambda_p\, v_h v'}{\lambda_\Phi\, v'^2 - \lambda_H\, v_h^2}$$

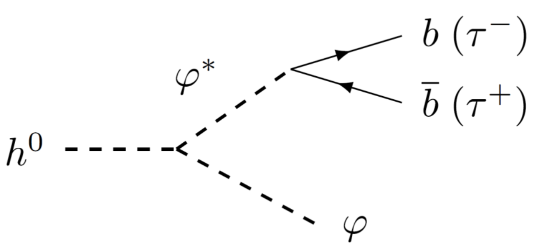
- Denote scalar mass eigenstates as φ and h^0
  - Production cross sections almost factorize according to SM Higgs-like content vs. NP ϕ-like content, except VBF modes
  - Most decay rates almost factorize similarly
    - Important exception: $\varphi \to \gamma\gamma$

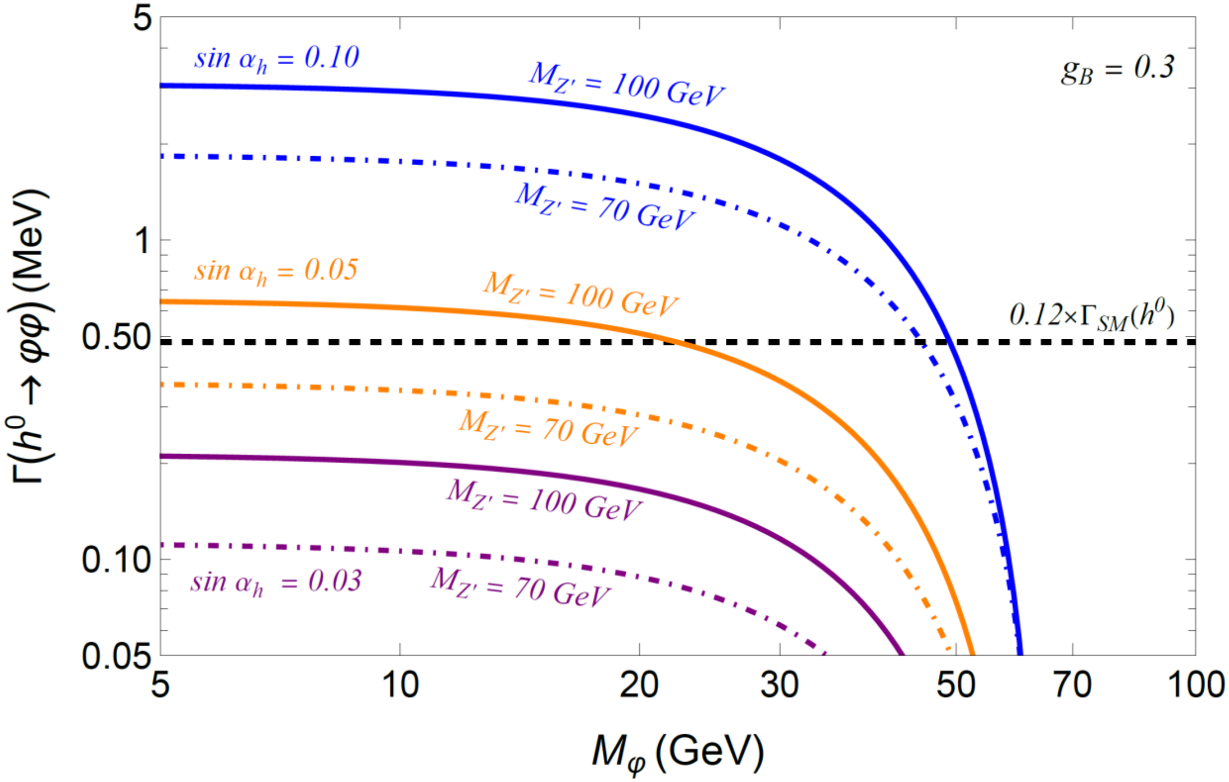
Cross sections with Higgs mixing



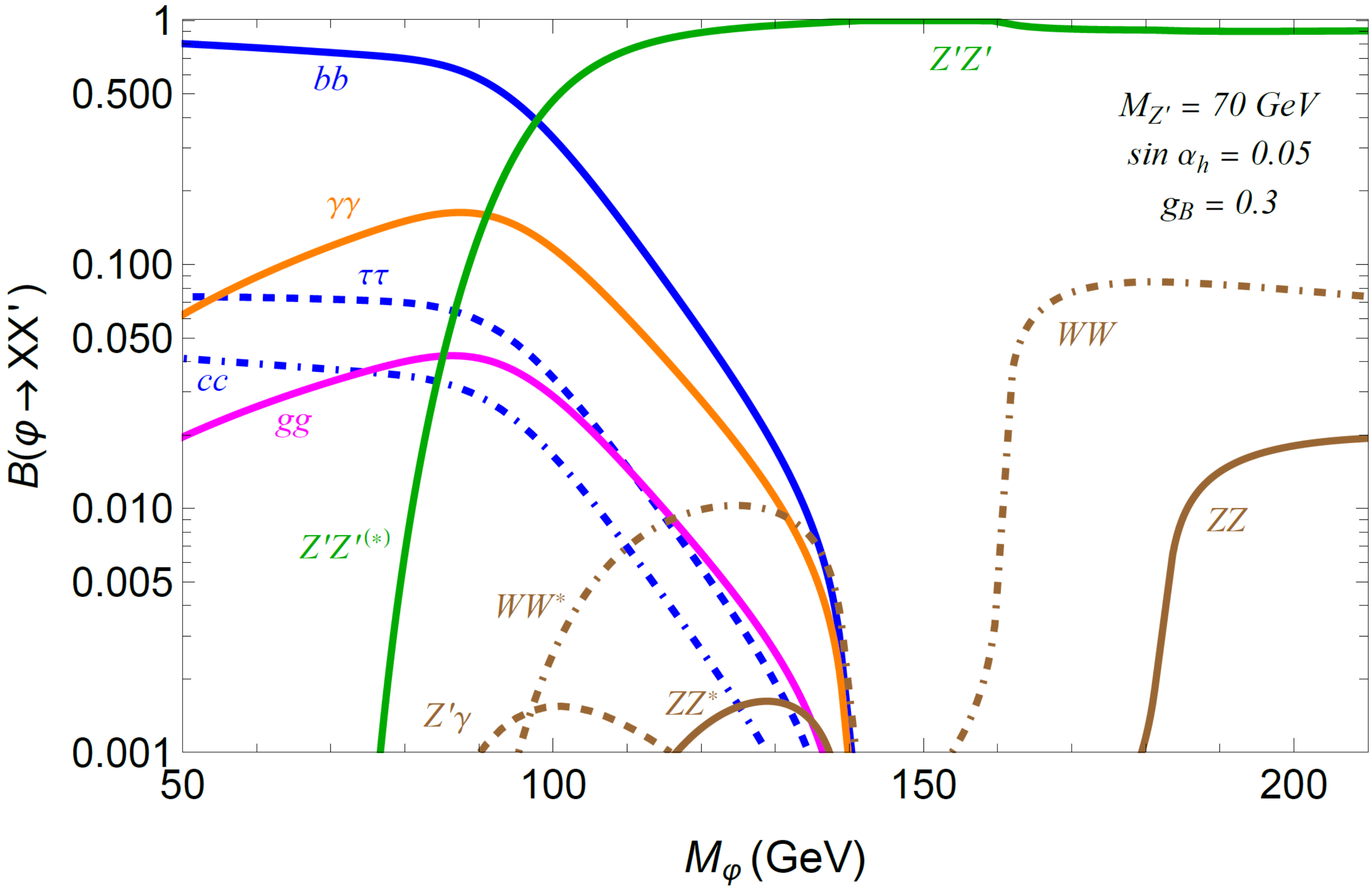
Effect on exotic Higgs decay

- For $M_\phi < m_h / 2$, must include induced exotic decay constraints

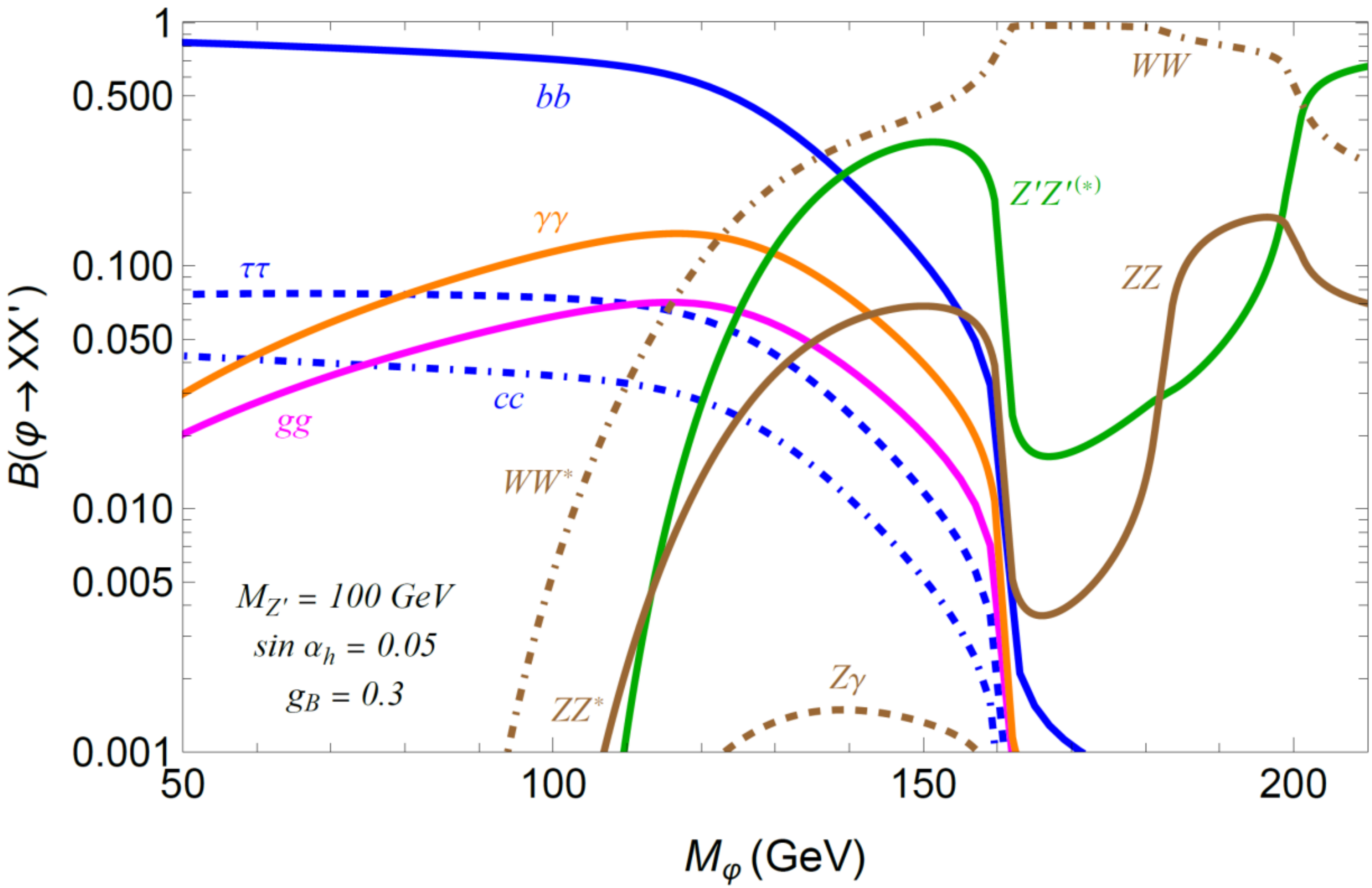




φ decays with h_{SM} mixing ($M_{Z'} = 70$ GeV)

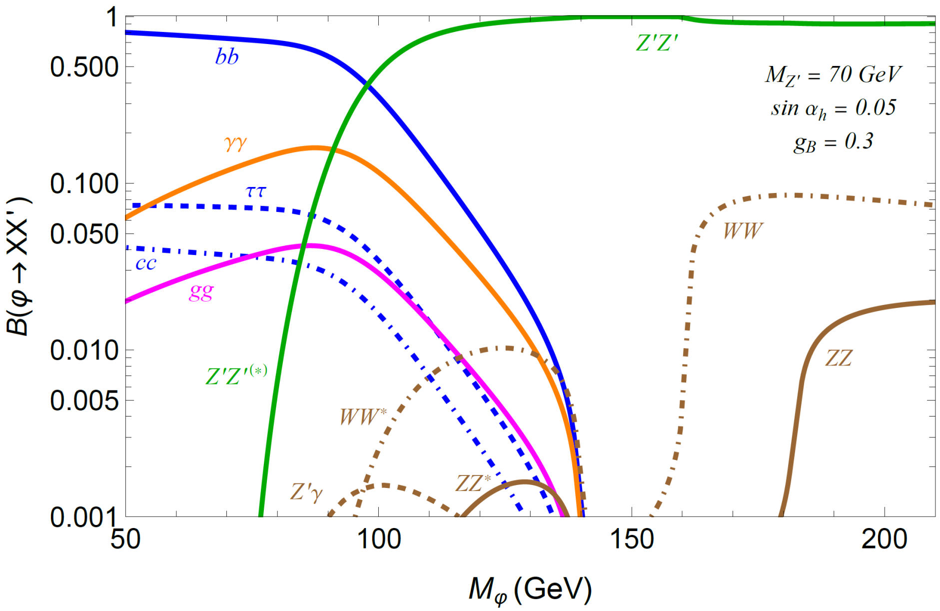


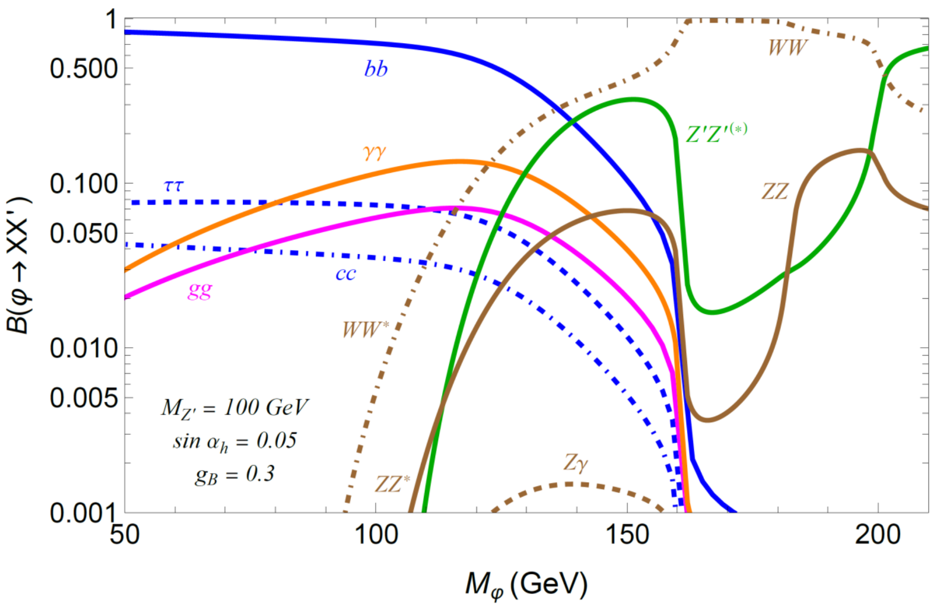
φ decays with h_{SM} mixing ($M_{Z'} = 100$ GeV)



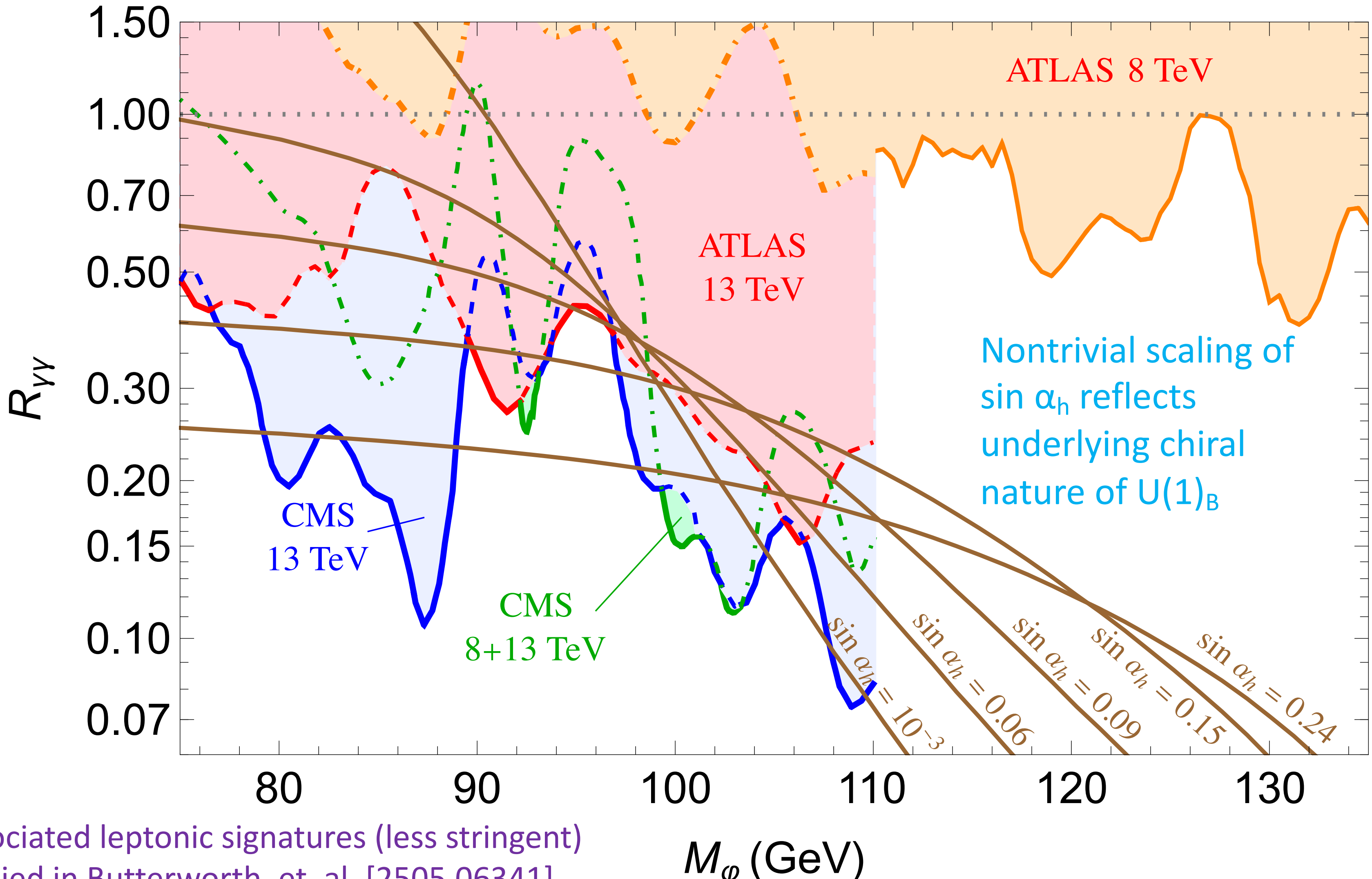
φ decays with h_{SM}: Comparison

- Intermediate mass behavior depends significantly on the $M_{Z'}$ vs. (M_W, M_Z) relative mass ordering





Leading constraints from $R_{\gamma\gamma}$



Nontrivial scaling of sin α_h reflects underlying chiral nature of $U(1)_B$

Associated leptonic signatures (less stringent) studied in Butterworth, et. al. [2505.06341]

Probing New U(1) Gauge Symmetries via Exotic Z → Z′ γ

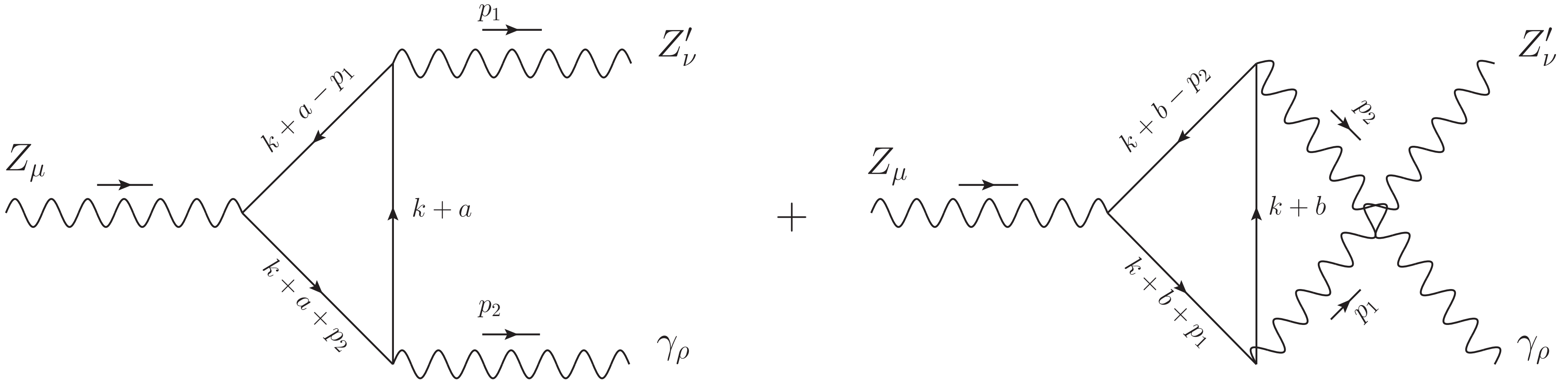
Lisa Michaels, FY, JHEP **03** (2021) [2010.00012]

A New Method for Loop Calculations Involving γ_5

FY, [2602.xxxxx]

Triple gauge boson vertex with chiral couplings

- Another important critical one-loop effective amplitude to calculate is the Z-Z′-γ vertex
  - Typically studied via 4-divergences for anomaly cancellation



  - Following Weinberg and Dedes, Suxho, allow each diagram to be shifted by $a^\mu = -b^\mu = z\, p_1^\mu + w\, p_2^\mu$, using dim. reg. and naïve γ^5

Dedes, Suxho, Phys. Rev. **D85** (2012) [1202.4940]

Triple gauge boson vertex with chiral couplings

- Vertex form factor decomposition (Lorentz-covariance)

$$\Gamma^{\mu\nu\rho}(p_1, p_2; w, z) =$$
$$F_1(p_1,p_2)\epsilon^{\nu\rho|p_1||p_2|}p_1^\mu + F_2(p_1,p_2)\epsilon^{\nu\rho|p_1||p_2|}p_2^\mu + F_3(p_1,p_2)\epsilon^{\mu\rho|p_1||p_2|}p_1^\nu + F_4(p_1,p_2)\epsilon^{\mu\rho|p_1||p_2|}p_2^\nu$$
$$+F_5(p_1,p_2)\epsilon^{\mu\nu|p_1||p_2|}p_1^\rho + F_6(p_1,p_2)\epsilon^{\mu\nu|p_1||p_2|}p_2^\rho + G_1(p_1,p_2;w)\epsilon^{\mu\nu\rho\sigma}p_{1\sigma} + G_2(p_1,p_2;z)\epsilon^{\mu\nu\rho\sigma}p_{2\sigma} \ ,$$

  - The momentum-shift dependence in vertex is carried in G_1 and G_2 form factors

- Overcomplete basis: can eliminate F_1 and F_2 by redefining F_3, … F_6 and G_1 and G_2

$$-p_1^\mu\epsilon^{\nu\rho|p_1||p_2|} = -p_1^\nu\,\epsilon^{\mu\rho|p_1||p_2|} + p_1^\rho\,\epsilon^{\mu\nu|p_1||p_2|} + \epsilon^{\mu\nu\rho\alpha}\left((p_1\cdot p_2)\,p_{1\alpha} - p_1^2\,p_{2\alpha}\right)$$
$$-p_2^\mu\epsilon^{\nu\rho|p_1||p_2|} = -p_2^\nu\,\epsilon^{\mu\rho|p_1||p_2|} + p_2^\rho\,\epsilon^{\mu\nu|p_1||p_2|} - \epsilon^{\mu\nu\rho\alpha}\left((p_1\cdot p_2)\,p_{2\alpha} - p_2^2\,p_{1\alpha}\right)$$

Dedes, Suxho, Phys. Rev. **D85** (2012) [1202.4940]

Triple gauge boson vertex with chiral couplings

- Vertex form factor decomposition (Lorentz-covariance)

$$\Gamma^{\mu\nu\rho}(p_1,p_2;w,z) = F_1(p_1,p_2)\epsilon^{\nu\rho|p_1||p_2|}p_1^\mu + F_2(p_1,p_2)\epsilon^{\nu\rho|p_1||p_2|}p_2^\mu + F_3(p_1,p_2)\epsilon^{\mu\rho|p_1||p_2|}p_1^\nu + F_4(p_1,p_2)\epsilon^{\mu\rho|p_1||p_2|}p_2^\nu + F_5(p_1,p_2)\epsilon^{\mu\nu|p_1||p_2|}p_1^\rho + F_6(p_1,p_2)\epsilon^{\mu\nu|p_1||p_2|}p_2^\rho + G_1(p_1,p_2;w)\epsilon^{\mu\nu\rho\sigma}p_{1\sigma} + G_2(p_1,p_2;z)\epsilon^{\mu\nu\rho\sigma}p_{2\sigma} \ ,$$

  - The momentum-shift dependence in vertex is carried in G_1 and G_2 form factors

- Ward identities see 4-divergence dependence on form factors

$$(p_{1\mu}+p_{2\mu})\Gamma^{\mu\nu\rho} = (G_2' - G_1')\,\epsilon^{\nu\rho|p_1||p_2|} \ ,$$

$$-p_{1\nu}\Gamma^{\mu\nu\rho} = (-F_3'\,p_1^2 - F_4'\,p_1\cdot p_2 + G_2')\epsilon^{\mu\rho|p_1||p_2|}$$

$$-p_{2\rho}\Gamma^{\mu\nu\rho} = (-F_5'\,p_1\cdot p_2 - F_6'\,p_2^2 + G_1')\epsilon^{\mu\nu|p_1||p_2|}$$

Triple gauge boson vertex with chiral couplings

- For our specific case, the vector and axial-vector Z and Z′ couplings of the virtual fermions appear as

$$(p_{1\mu} + p_{2\mu})\,\Gamma^{\mu\nu\rho} = \frac{Q e_{\rm EM} g g_X}{4\pi^2 c_W}\epsilon^{\nu\rho|p_1||p_2|}((w-z)(g_v^{Z'} g_a^Z + g_v^Z g_a^{Z'}) + 4m^2 g_v^{Z'} g_a^Z C_0(m))$$

$$-p_{1\nu}\Gamma^{\mu\nu\rho} = \frac{Q e_{\rm EM} g g_X}{4\pi^2 c_W}\epsilon^{\mu\rho|p_1||p_2|}((w-1)(g_v^{Z'} g_a^Z + g_v^Z g_a^{Z'}) - 4m^2 g_v^Z g_a^{Z'} C_0(m))$$

$$-p_{2\rho}\Gamma^{\mu\nu\rho} = \frac{Q e_{\rm EM} g g_X}{4\pi^2 c_W}\epsilon^{\mu\nu|p_1||p_2|}(z+1)(g_v^{Z'} g_a^Z + g_v^Z g_a^{Z'})\,,$$

  - Dictates “non-decoupling” behavior of virtual fermions via $m^2 C_0(m) \to -1/2$ in heavy m limit
- Literature typically adopts a fixed choice of w, z to define “covariant” anomaly or “consistent” anomaly
  - Determines the corresponding Wess-Zumino effective operator

Preskill, Annals Phys. **210** (1991)

An observable: chiral gauge anomaly

- Point of departure: construct observable for exotic decay of Z → Z′ γ
  - New on-shell amplitude only possible in U(1) gauge extensions
  - Sum over all SM fermions and anomalons necessarily eliminates w, z dependence in total vertex function
    - Conjecture: requiring observables to be w- and z-independent is equivalent(!) to anomaly cancellation condition

FY, [2602.xxxxx]

$$\Gamma(Z \to Z'_B \gamma) = \frac{\alpha_{\rm EM}\alpha\alpha_X}{96\pi^2 c_W^2}\frac{m'^2_Z}{m_Z}\left(1 - \frac{m^4_{Z'}}{m^4_Z}\right)$$

$$\left| - \sum_{f\in \rm SM} T_3(f) Q^e_f \left[\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\left(B_0(m_Z^2, m_f) - B_0(m_{Z'}^2, m_f)\right) + 2m_f^2 C_0(m_f)\right]\right.$$

$$\left. + 3\left(\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\left(B_0(m_Z^2, M) - B_0(m_{Z'}^2, M)\right) + 2M^2\frac{m_Z^2}{m_{Z'}^2} C_0(M)\right)\right|^2 ,$$

Dim. reg., naïve γ^5, and momentum-shift independence

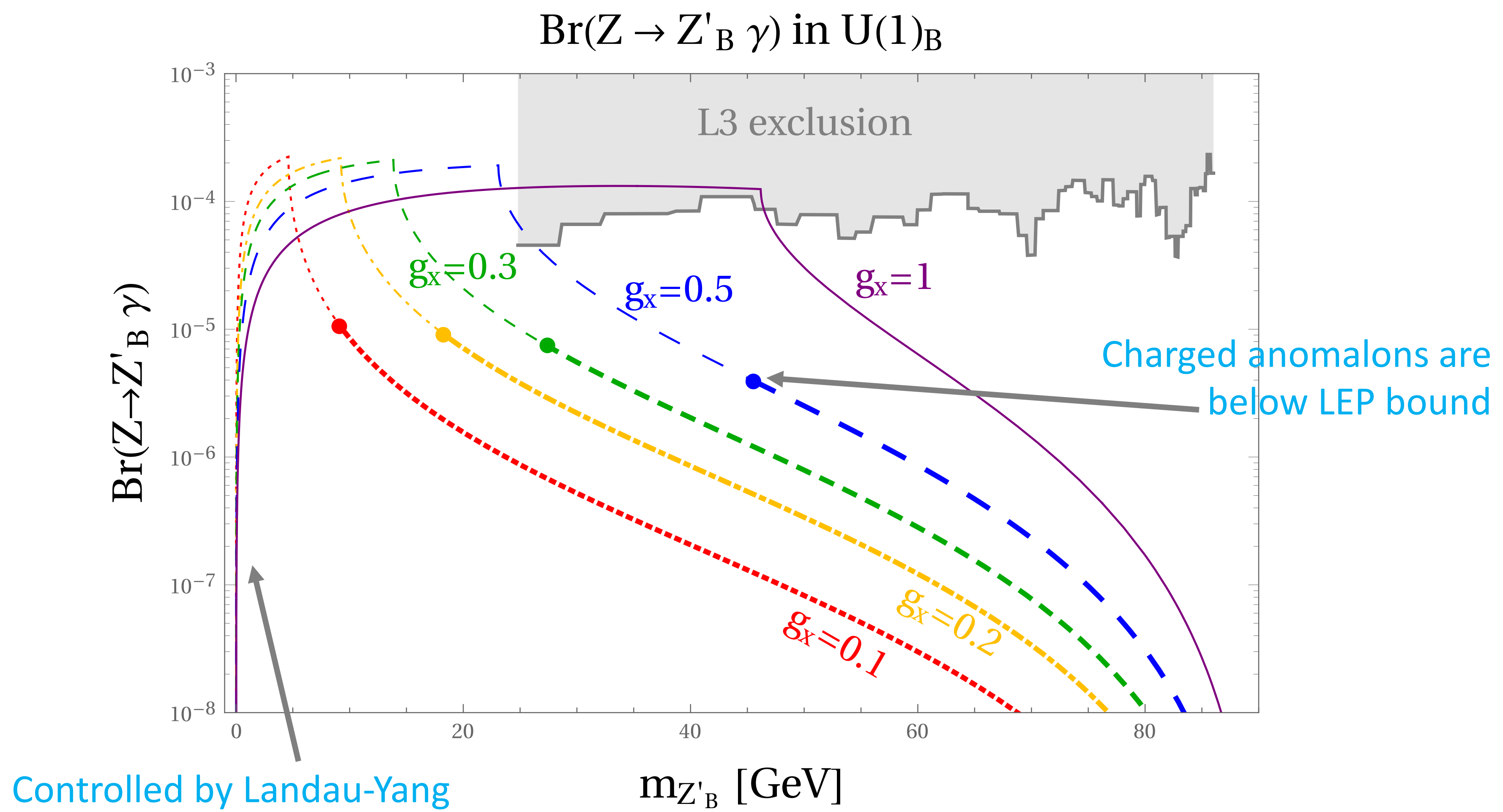
- For $Z \to Z' \gamma$, we showed that an anomaly-free fermion content, using dim. reg., naïve γ^5 and allowing w- and z-momentum-shift dependence, results in a w- and z- independent result
  - Each individual fermion contribution carries momentum-shift dependence and is anomalous
- Conjecture: requiring observables to be w- and z-independent is equivalent(!) to anomaly cancellation condition

FY, [2602.xxxxx]

  - Closest analogy: shift-dependence in loops with chiral couplings is akin to R_ξ-dependence in SSB loop calculations
  - Provides a new method to handle γ^5 in loop calculations (compared to BHMV, Larin, KKR, etc.), especially relevant for (N)NLO EW precision calculations
  - Restores the central conceit of dim. reg. that finite momentum shifts of loop momenta do not affect calculations

An observable: chiral gauge anomaly

- Exotic Z decay is emblematic of U(1)-gauge extensions



An observable chiral gauge **anomaly**

- Can also calculate a curious feature: contribution for one generation of a mass-degenerate set of SM fermions and $U(1)_B$ anomalons, consider large mass limit

$$\Gamma(Z \to Z'_B \gamma)^{\text{non-anom.}} = \frac{3\,\alpha_{\text{EM}} \alpha \alpha_X}{32\,\pi^2 c_W^2} \frac{(m_Z^2 - m_{Z'}^2)^2}{m_Z m_{Z'}^2} \left(1 - \frac{m_{Z'}^4}{m_Z^4}\right)$$

  – Does not decouple, effectively counts the mixed gauge anomaly between chiral SM and $U(1)_B$ gauge symmetries

In contrast to B-L or $L_\mu - L_\tau$ symmetries

  – Future work: obeys Adler-Bardeen non-renormalization theorem?

Conclusions

- Effective descriptions of chiral new physics carries rich phenomenology and field theory structure
  - Many features for ϕ collider phenomenology reminiscent of Higgs phenomenology, albeit with important interference effects
  - Effective operator construction for Z-Z′-γ vertex demonstrates a new formulation of chiral anomaly cancellation
- Beyond effective theories, new U(1)′ gauge symmetries offer novel field-theoretic results
  - *e.g.* nearly mass-degenerate Z-Z′ bosons require careful phenomenological treatment to extract consistent constraints
  - Novel aspects of avoided crossing and dispersive seesaw effect

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